HOW THE URBAN ENVIRONMENT AFFECTS THE MICROCLIMATE AND THE BUILDING ENERGY DEMAND FOR THE CITY OF ROME

by

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Urban heat island has significant impacts on buildings' energy consumption. The phenomenon is associated with increased urban air temperatures compared to the air temperature of the surrounding rural or suburban areas. The ambient air temperature growth due to climate changes and the urban heat island phenomenon are dramatically increasing the cooling demand in buildings. This is worsened by irradiation conditions, construction technologies, and subjective comfort expectations. This paper examines the impact of the urban environment on the energy demand of buildings, considering the case of two districts of the city of Rome, Italy: one is representative of a central zone, the other of a rural zone. Weather data were then used to calculate the thermal demand of a typical Italian building, ideally located in the monitored areas of the city. Standalone building with modified weather file was modeled in TRNSYS. Results show that urban heat island intensity causes an increase in cooling demand up to +33% for the urban area (+20% for the rural area) compared to the demand calculated using weather data from airportual areas. On the other hand, urban heat island intensity has a positive effect on heating demand which turns out to decrease up to –32% for the urban area (–14% for the rural area).

Keywords: *urban heat island, street canyon, thermal energy demand, TRNSYS*

Introduction

One of the major concerns of our days is to reduce energy consumption and the environmental impact of cities and buildings. In Italy, this problem is mostly associated with the summer season. The common use of air-conditioning in residential buildings has led to a fast increase of electricity consumption over the last few decades.

Urban growth has meant that buildings and other infrastructures substitute open land and vegetation [1, 2]. This has influenced the energy performance of buildings and human comfort. This growth leads to the development of the so called urban heat island (UHI) phenomenon, characterized by higher temperatures in the densely constructed areas than the ones of the rural neighborhood. These temperature differences can range between 1-3 °C in cities with one million or more inhabitants [3].

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The combination of global warming with the UHI effect makes the energy issue particularly worrying. The predicted climate scenarios for the next 100 years [4] foresee an increase of tropical nights (>20 °C) and hot days (>35 °C) for the Mediterranean basin.

The effect of the UHI, therefore, is the result of the mutation of our cities, which sees the reduction of vegetation and evapotranspiration, a greater prevalence of opaque surfaces with low albedo and an increased production of anthropogenic heat [5, 6]. Higher temperatures cause a significant increase in the energy consumption of buildings, since they affect the already onerous cooling demand [7-12]. In the South America Pacific coast, the UHI causes arise in the cooling energy demand ranging from +15% to +20% [13], while in Beijing [14], it has been reported that the UHI has increased the cooling energy demand by +11% (+7% considering the peak cooling load) and has reduced the heating energy demand by +16% (−9% if the peak heating load is considered).

The UHI intensity is therefore a decisive variable for the estimation of buildings energy performance. Non-theless, it is still rather ignored in the practice of energy assessment. The aim of this paper is to quantify the impact of UHI intensity on the thermal energy demand for residential buildings. To this purpose, the city of Rome has been selected as case study. The monitored district is characterized by different location: *Via Lanciani* is representative of a central zone and *Ponte di Nona* is considered as a rural zone.

A strong UHI intensity was recorded in summer during the daytime, when the temperature difference between rural weather stations and urban stations reached up to 3 °C in locations far away from neighborhood buildings. During the night time, the temperature difference was smaller than 1 °C. Kolokotsa *et al.* [15] studied the UHI in the city of Hania, Greece, finding a maximum daily UHI intensity of 8 °C and an average urban-rural temperature difference of almost 2.6 °C. More recently, Giannopoulou *et al.* [16] reported a variation of the UHI intensity in Athens between 3.0 °C and 5.3 °C during the day time and between 1.3 °C and 2.3 °C during the night time.

A further study was conducted by Giannaros and Melas [17] in the coastal city of Thessaloniki, who identified a maximum UHI intensity between 2 °C and 4 °C. However, results on this subject are still contradictory, being strictly dependent on the reference climate and the methodologies adopted in the studies. During the last 30 years many types of software able to simulate dynamically the behavior of the buildings have been developed, such as EnergyPlus [18] and TRNSYS [19]. The relevance of Building Energy Simulation (BES) is the estimation of the heating and cooling demand of buildings in order to design active and passive systems [20-24]. For the calculation of thermal energy demands, BES tools need a representative weather file from which such parameters as temperature, humidity, solar radiation, wind direction, speed, and their hourly variation can be obtained. These files are normally obtained from meteorological stations located in suburban or rural areas.

Therefore, standard meteorological data seem to be rather inaccurate to run energy simulations of buildings in urban areas, since they refer to out-of-town weather stations (usually airports) that cannot identify the UHI effect [25-27].

Methodology

In this paper the influence of the UHI on the heating and cooling demand of a three-floor residential building was analyzed. Weather station data for the rural zone of Ponte Di Nona will be compared with weather file from the almost central zone of Lanciani. The temperature's differences between Ponte di Nona and Lanciani are defined as the UHI index. The BES software used to perform numerical simulations in this work is TRNSYS 17, a transient multi-zone

3-D construction code that can dynamically simulate the energy behavior of a building with time steps of less than one hour.

Figure 1 show the aerial view of the two zones, where we can observe the main characteristics of the urban texture. The selected zones are: Lanciani and Ponte di Nona. Air temperature is continuously measured in each of the two selected zones. Red dots in fig. 1 mark the weather stations positions in the two areas. At first, data are analyzed in order to identify temperature rising in the detected urban areas with respect to the reference station. The UHI effect is therefore quantified. Regione Lazio ARSIAL site [28], which has a monitoring network currently consisting of 93 electronic stations located on the entire regional territory that transmit the acquired measures on a daily basis, has provided the required climate data. This allowed us to create custom weather inputs to calculate the cooling and heating energy demand in a residential building.

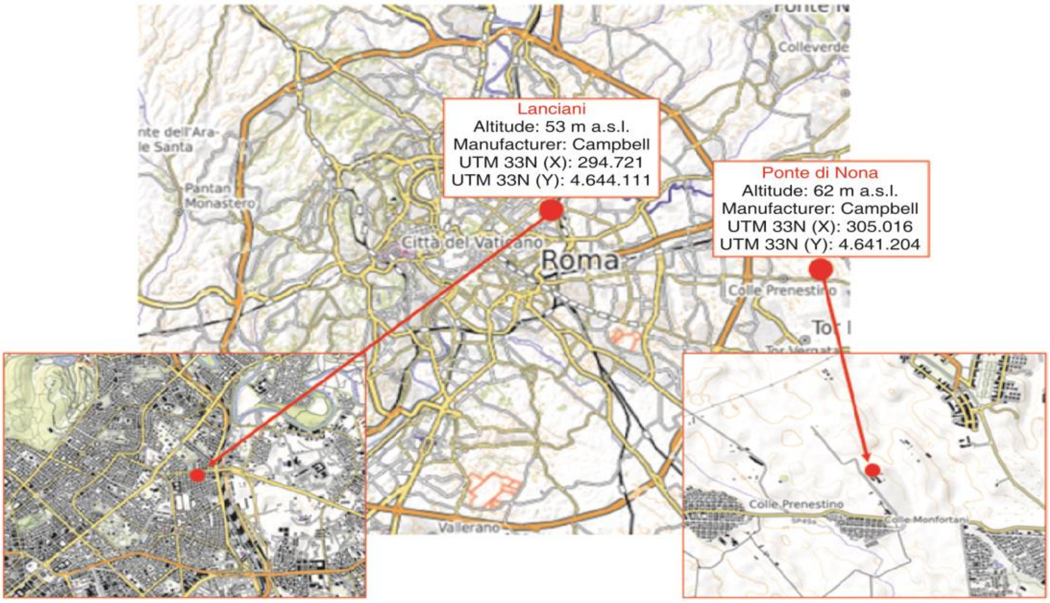

Figure 1. Aerial view of the two selected zones: Lanciani and Ponte di Nona; the measurement point is marked with a red dot

Numerical model

In TRNSYS, conduction heat flow through envelope components is modeled using the 1-D transfer functions. Constant values of the convection heat transfer coefficient (CHTC) convection factor were chosen according to the standards (CHTC equal to 17.8 W/m²K, while it is equal to 3 W/m²K for indoor surfaces) [29]. Radiative heat flows are modeled differently for external and internal surfaces. At a deeper level, solar irradiation on envelope elements is considered as a gain while longwave radiation is treated as a heat loss towards the cold sky. Figure 2 shows the characteristics of the building studied: the length is 110.5 m, since one of the purposes was to represent a long building with similar adjacent apartments but also to minimize the effects of the boundary conditions on the short sides of the building.

Both building's height, H, and width, W, are 13.5 m. The short side walls are modeled adiabatic assuming they are continuous, thus modeling a long row of identical thermal zones.

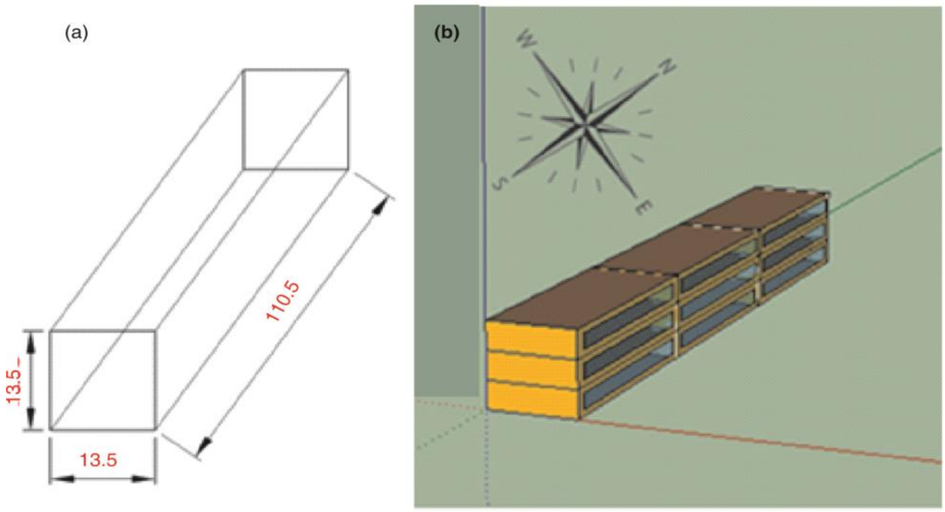

Figure 2. Geometrical features (a) and 3D overview of the street canyon (b)

Absorptivity factor of the building façades is $\alpha = 0.6$, while albedo is $\rho = 0.2$ The orientation of the building is S-N, the ratio of transparent/opaque surfaces is $A_{\mathrm{tr}}/A_{\mathrm{op}} = 0.5$.

Building energy simulation model

Building envelope opaque and transparent elements characteristics are shown in tab. 1.

In tab. 1, g stands for window's solar factor, α for absorptivity coefficient, and ε for thermal emissivity. Internal gains due to the lighting system, electrical devices, users and occupancy schedules are set according to residential use as indicated in [30].

Table 1. Main features of construction envelope elements

Envelope element	Materials	Thickness [m]	U [Wm^{-2}K^{-1}]	g	α	ε
Walls	Plaster, brick, insulation	0.44	0.36		0.6	0.9
Roof	Plaster, concrete, screed, insulation	0.37	0.32		0.6	0.9
Pavement	Ceramics, concrete, isolation, plaster	0.54	0.34		0.6	0.9
Windows	Glass, wood	–	1.40	0.6		0.84

The gains reported in tab. 2 are related to the total floor area. The presence of the users is considered for 24 hours per day. The usage schedule for the electrical devices is set "on" from 8.00 to 24.00 while for lights is set "on" from 17.00 to 24.00.

The daily natural ventilation rate is 0.3 vol/h while the envelope infiltration rate is assumed to be 0.2 vol/h while during night-time only the infiltration rate is imposed. Weather data for the city of Rome are used as input for the BES where the heating period is imposed to be from November, 1st to April, 15th and the cooling period is not imposed by laws.

Table 2. Specific values of internal gains

	Persons [Wm^{-2}]	Devices [Wm^{-2}]	Lights [Wm^{-2}]
Radiative	1.51	0.35	3.5
Convective	3.01	1.05	1.5

Thus, the space cooling and space heating demands are determined considering the room air temperatures controlled to be at 20 °C during the winter and 26 °C during summer (considering as cooling period the days in which the internal temperature exceeds 26 °C).

Numerical results

Urban heat island

The UHI intensity growth is observed after sunset (hrs: 18:00-30:00), as shown in figs. 3(a) and 3(b).

This phenomenon is caused by:

- physical characteristics of the surfaces, such as concrete and asphalt, that absorb rather than reflecting solar radiation,
- lack of natural evaporative surfaces (vegetation) that, in rural areas, contribute to maintain a stable energy balance,
- presence of vertical surface that both provide an increasing in absorbing and reflecting solar radiation as well as blocking winds that could contribute to the lowering of the temperature,
- human activities that mainly consist in heat produced by heating and cooling plants for buildings, industrial activities, vehicles, *etc*., and
- high level of pollutants that alter the radiative nature of the atmosphere.

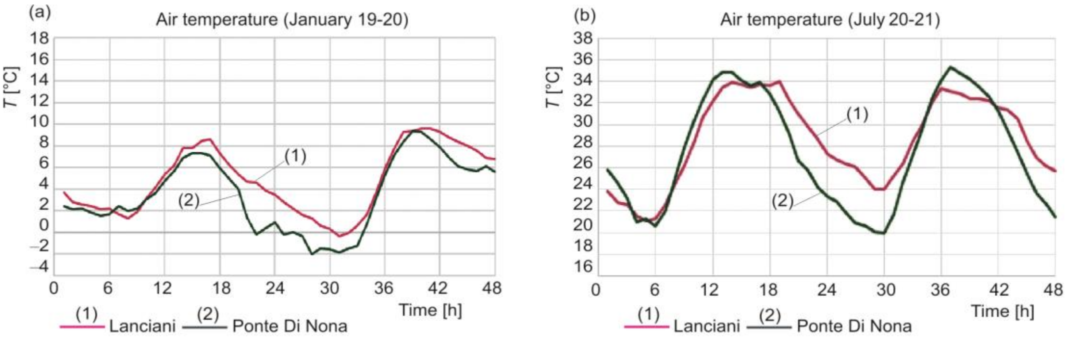

Figure 3. Air temperature profile for two consecutive days for Lanciani and Ponte di Nona; (a) winter case, (b) summer case

Figure 4 shows UHI intensity profile, *i. e*. the hourly daily averaged differences in temperatures for each months of the year 2016. As we can see, a higher positive UHI intensity index during the night hours (between 01:00-07:00 and 21:00-24:00, with a peak that exceeds 3 °C), was detected. This effect is most noticeable during the summer season.

The higher negative UHI intensity index is detected in the same period of the year as well (from June to August), but in the central hours of the day, when the solar radiation effect is at its peak, in agreement with Runnals and Oke [31].

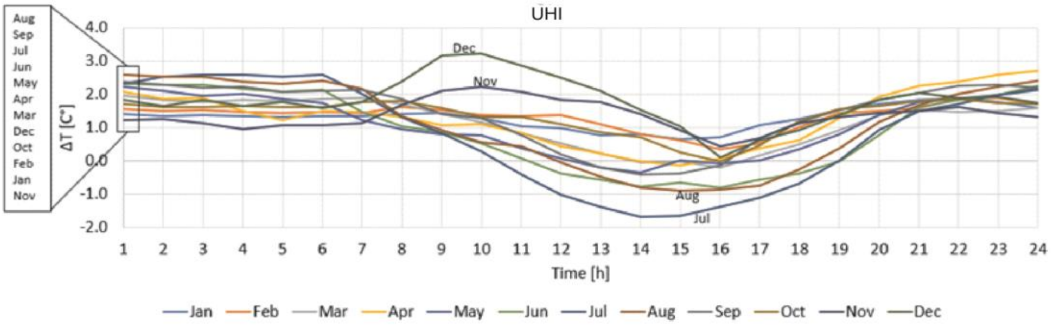

Figure 4. Average diurnal UHI intensity schedules for each month of the year
(*for colour image see journal web site*)

Building thermal energy demand

Figure 5 shows a higher heating demand for an isolated building located in Fiumicino and Ciampino which, for what has been said, are not affected by the UHI phenomenon, since they are both aeroportual areas. For buildings located in via Lanciani, where air temperature is higher due to a greater urban density, anthropogenic heat and less vegetation, the heating demand is lower. Ponte di Nona, on the other hand, shows an intermediate behaviour. This results in a decrease in heating demand from –4% for Ponte di Nona up to –24% for Lanciani compared to Fiumicino and in a decrease from –14% for Ponte di Nona and –32% for Lanciani compared to Ciampino, fig. 5(a).

The UHI phenomenon brings an advantage in winter but the same cannot be said for summer, during which cooling demand is generally higher. As a matter of fact, simulations show cooling demand increase up to +20% for Ponte di Nona and up to +33% for Lanciani, compared to Fiumicino, and increase from +18% for Ponte di Nona and +31% for Lanciani, compared to Ciampino, fig. 5(b).

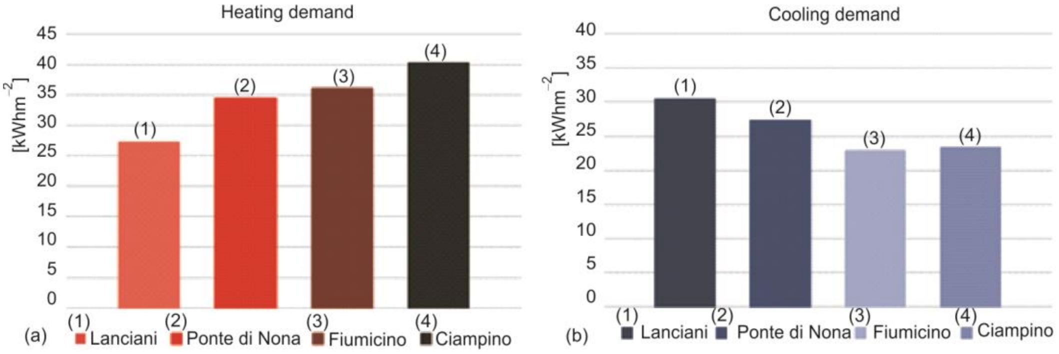

Figure 5. (a) Heating demand and (b) cooling demand for Lanciani, Ponte di Nona, Fiumicino, and Ciampino

Conclusions

The investigation of UHI effects requires skills in different subjects such as urban planning, landscape, architecture, and building materials science. The work analyses climatic conditions in two neighbourhoods of Rome, in order to assess the presence of UHI effect and its impact on buildings' energy performance. The range of variability of UHI intensity and the corresponding variation range for cooling and heating loads for residential buildings in the urban context are investigated.

Weather data were obtained for the entire year of 2016 from the Regione Lazio Arsial website, regarding Lanciani and Ponte di Nona. For the aeroportual areas of Fiumicino and Ciampino, we used embedded data from TRNSYS 17 library. In this way we can assess the error that is committed in buildings' energy demand simulation when we use BES software and their pre-set data. The study was conducted using a BES software on a building with envelope thermal isolation values in accordance with current laws. The analysis shows that meteorological data obtained from operational weather stations located outside the city, such as the airports, are inaccurate to perform energy simulations of buildings in an urban context, where the cooling demand will be even greater. Results show that UHI intensity causes an increase in cooling demand up to +20% for Ponte di Nona and an even higher (+33%) for Lanciani, if compared to Fiumicino, and increases from +18% for Ponte di Nona and +31% for Lanciani, if compared to Ciampino. On the other hand, UHI intensity has a positive effect on heating demand which turns out to decrease up to –4% for the rural area (Ponte di Nona) and up to –24% for Lanciani central area compared to Fiumicino and in a decrease from –14% for Ponte di Nona and –32% for Lanciani compared to Ciampino. Therefore, these values represent the error that can be made in energy demand computing considering airport temperatures instead of the actual urban ones. Overall, the availability of more specific meteorological information for big cities is desirable. Such availability can be used to facilitate the generation of a more consistent and realistic climate database for improving the predictive accuracy of building simulation models, to improve the estimation of operational energy costs, indoor environmental conditions and make more rational assessments for energy saving measures in existing buildings. In conclusion, the main problem with the UHI is that each city has its own urban environment and this raise the need for more specific data that can satisfy each case's request. The most relevant issue concerning the UHI is that conditions are not identical in every urban environment. Cities around the world are deeply different, and solutions must be found that meet the needs of each individual city around the globe.

Nomenclature

A_{op} – opaque surfaces
A_{tr} – transparent surfaces
g – window's solar factor
H – height of building
U – overall heat transfer coefficient, [$Wm^{-2}K^{-1}$]
W – width of building

Greek symbols

α – absorptivity coefficient
ε – thermal emissivity
ρ – albedo

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